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Information content of Umkehr and solar backscattered ultraviolet (SBUV) 2 satellite data for ozone trends and solar responses in the stratosphere

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Abstract. Within the past few years, several papers have been published which present updated profile ozone trends from the recently revised ground-based Umkehr record [*Miller et al.*, 1995] and the combined Nimbus 7 solar backscattered ultraviolet (SBUV) and NOAA 11 SBUV 2 satellite data record [*Hollandsworth et al.*, 1995; *Miller et al.*, 1996]. Within these papers, however, there has remained an overriding question as to the actual information content of the measurement systems and their ability to detect atmospheric responses. In this paper, we compare the ozone trends and responses to the 11-year solar cycle (derived from model and/or data specifications of these effects) to results of forward model/retrieval algorithm computations through the algorithms. We consider data at northern midlatitudes (30°–50°N) so that we may compare the satellite results with those of the ground-based systems. Our results indicate that the Umkehr data contain only four independent pieces of information in the vertical and that the SBUV system contains five. In particular, we find that consideration should be restricted to the following regions; Umkehr: the sum of Umkehr layers 1–5, and layers 6, 7, and 8+ (the sum of layers 8 and above), SBUV: the sum of layers 1–5, and layers 6, 7, 8, and 9+ (the sum of layers 9 and above). Additionally, we compare the actual trends and solar coefficients derived in these layers for the periods 1968–1991 and 1979–1991 for the Umkehr and SBUV data. Finally, we include within the latter comparisons the stratospheric aerosol and gas experiment (SAGE) I and II results from *Wang et al.* [1996] and the computations from the ozonesondes.

Introduction

Accurate knowledge of the ozone trends as a function of altitude is necessary to understand the effects of natural and anthropogenic influences and to validate atmospheric chemistry models used to predict changes in stratospheric ozone. In addition, the vertical distribution of ozone losses determines how global stratospheric temperatures will be affected by ozone depletion [*Logan*, 1994, and references therein; *Miller et al.*, 1992; *Ramaswamy et al.*, 1996]. Profile ozone is difficult to measure, however, and there are few sources of reliable long-term data. Recent literature has increasingly focused on the comparison of estimated trends in profile ozone measurements from a variety of instruments [e.g., *World Meteorological Organization (WMO)*, 1995; *Claude et al.*, 1994; *McPeters et al.*, 1991; *DeLuisi et al.*, 1994; *Stolarski et al.*, 1992]. In one such study, *DeLuisi et al.* [1994] found good agreement between the trends derived from a simple least squares fit of profile ozone data (note that a fit to solar cycle was not included) at five midlatitude Umkehr stations and the 30°–50°N zonal-mean Nimbus 7 solar backscattered ultraviolet (SBUV) measurements. The authors found that over the 1979–1990 time period the trends in the Umkehr data were about 2% per decade more negative in layers 3 and 4 (~15–20 km) and approximately 2% per decade less negative in layers 5 and 6 (~25–30 km) compared to trends derived from the SBUV data. The Umkehr data have since been reprocessed with an updated algorithm [*Mateer and DeLuisi*, 1992] and revised total ozone values [*Bojkov et al.*, 1990]. Comparisons between the trends derived from the old and new algorithm show that the lower stratospheric trends are substantially less negative using the new algorithm, while the trends in the middle stratosphere are slightly more negative [*Reinsel et al.*, 1994]. More recently, *Mateer et al.* [1996] have examined the effect of the a priori profiles on the Umkehr algorithm in the lower stratosphere through comparison with balloonsonde observations. Through their results and consideration of the averaging kernels, they conclude that trend information at the top and bottom of the retrieved profiles is

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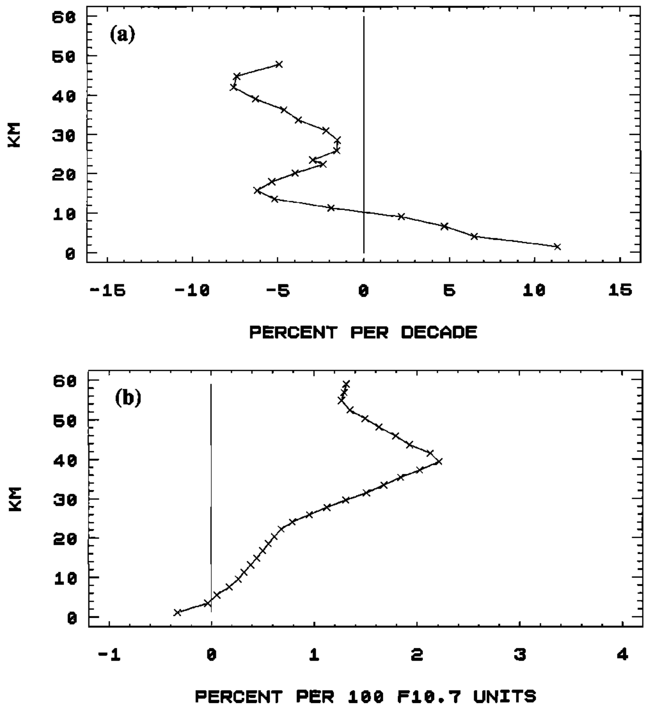

Figure 1. (a) Specified ozone trend perturbations as a function of altitude derived from combination of computations from ozonesondes up to 25 km and SAGE above. Units are percent per decade. (b) Specified solar response perturbations as a function of altitude from *Jackman et al.* [1996].

available in only broad altitude regions and recommend that the trend data be considered in the sum of layers 1–3, and layers 4, 5, 6, 7, and 8+. In a similar vein, *Bhartia et al.* [1996] have studied the information content of the SBUV system and find somewhat similar results as to the vertical profile information. Their recommendation is that studies of long-term trends using the SBUV data be restricted to total ozone and the 1–20 mbar range for the vertical profiles. These studies, as indicated, focused on general perturbations to the ozone profile. With a considerable interest now being extended to possible solar effects in the lower stratosphere [*Hood et al.*, 1993; *Chandra and McPeters*, 1994; *McCormack and Hood*, 1996] it is important that the consideration of the system's information content be extended to both the solar effects and to the full extent of the stratosphere.

In this paper, we specify independent, reasonable profiles of ozone trends and solar effects from the surface through the stratosphere (in the sense that these profiles are realistic representations of these atmospheric variations) and utilize these profiles to evaluate the ability of both the SBUV and Umkehr systems to replicate the results. This is accomplished by calculating the radiance that each system should see from each perturbation profile utilizing a forward model and then employing the standard algorithm to retrieve the specified perturbation profile. In a perfect system the specified and retrieved perturbation profiles would coincide. As we will show, however, the profile perturbations do differ and this leads us to identify the areas over which the trends and solar coefficients can be derived effectively. Finally, we compare the actual trends and solar coefficients in the rederived layers from the SBUV and Umkehr systems along with those derived from the ozonesonde and newly rederived stratospheric aerosol and gas experiment (SAGE) data.

Data and Methods

We have initiated this study with the specification of independent, reasonable profiles of the trend and solar ozone response at northern hemisphere midlatitudes. For the trend profile we constructed a composite of the balloon ozonesonde trends up to about 25 km [*Miller et al.*, 1995] and the SAGE trends above that from *Wang et al.* [1996]. This composite is shown in Figure 1a. For the solar effect we have utilized the results of the Goddard Space Flight Center two-dimensional model described by *Jackman et al.* [1996] for the midlatitudes of the northern hemisphere. This is depicted in Figure 1b. We see from Figure 1 that the shapes of the two effects are quite different and represent a reasonable test of the information inherent in the SBUV and Umkehr observation plus algorithm systems.

The main limiting factor in developing the appropriate test cases of the vertical distribution of ozone trends is the requirement for full information from the surface through the upper stratosphere. While the SAGE data are global in nature, the ozonesondes are basically limited to the midlatitudes of the northern hemisphere [e.g., *Logan*, 1994]. Hence the test conducted here is limited to this restricted region. It does, however, indicate the magnitude of the possible effects and the requirements for awareness. We utilize published trend results from *Wang et al.* [1996], based on SAGE data, Version 5.93, where the authors have attempted to correct for recognized issues with the data. We are aware that the SAGE data have been reprocessed with Version 5.96 and that the trend results, when reanalyzed, may vary.

The ability of an SBUV or Umkehr instrument to monitor profiles of ozone trends was examined by using the trend profile described above as a perturbation to the standard ozone profile. A baseline retrieval was found by taking the standard profile and using a forward model [*Dave*, 1964; *Mateer and DeLuisi*, 1992; *Bhartia et al.*, 1996] radiative transfer code to compute the theoretical backscattered radiances at the top of the atmosphere or diffuse radiances at the ground for Umkehr. These computed radiances were then used as input to the standard retrieval code, and a retrieved profile was obtained. The standard profile was then perturbed by the estimated effect of 10 years of trend, and the forward model and retrieval process were repeated. The differences in the retrieved profiles were then compared to the differences in the initial profiles. A similar procedure was followed for the solar effect profiles.

A slightly modified version of the retrieval algorithm was used to perform the simulated SBUV retrievals. It included the first guess construction used in the operational version. This first guess uses the total ozone estimate from the measurements at the four longest wavelengths to interpolate a profile from a set of standard climatological profiles for the given latitude. This is one reason why an averaging kernel analysis is complicated for the SBUV retrievals. The total ozone is also carried along into the profile retrieval as a measurement in place of the four longer wavelengths. In this way the effect of the total ozone change has been included.

The results of the forward model also give an estimate of the changes in the radiance ratios (I/I_0 is the basic measurement utilized in the SBUV algorithm) one would expect to observe and thus an idea of the accuracy with which the calibration must be maintained. The differences in radiance ratios based on the profile trend composite are presented in Table 1. In this table we see that the radiance effects that have to be monitored are about 2% per decade at the shortest wavelength (highest altitude) and about 7% per decade at the longest wavelength (lowest altitude). As it appears that our basic ability is to maintain the SBUV system to an accuracy of about 3% per decade [*Bhartia et al.*, 1995], it is clear that our ability to monitor the observed (SAGE) ozone changes at the highest altitudes is somewhat limited.

Results

The results of these calculations are depicted in Figures 2a (trends) and 2b (solar); the Umkehr is in layers 1 to 9, and the SBUV is in layers 1 to 10. Examining the trend results, we see that both the SBUV and Umkehr systems lack independent information from the total ozone—a priori profiles in layers 1 through 5 and are unable to determine the specified profile change with much accuracy as previously noted by *Mateer and DeLuisi* [1992] and *Bhartia et al.* [1996]. In layers 6 and 7, however, both systems recover the specified changes. Above this the SBUV captures the relative peak quite well, whereas the Umkehr appears to lack information in layers 8 and above. Looking next at the solar profile in Figure 2b, we see that in the lower layers the results are very similar to those of the trends and both systems cannot resolve the full profile perturbation. Layers 6, 7, and 8 are quite consistent, but above this the retrievals diverge. The Umkehr appears to greatly underestimate the perturbation in layer 9, whereas SBUV in layer 9 has a slight overestimation and agrees well again in layer 10.

On the basis of these results as well as those given by averaging kernel analysis, it is clear that the information content of the two systems is fundamentally limited. For the Umkehr the indication is that the data should be considered as four pieces of information, the sum of layers 1–5, layers 6, 7, and the sum of layers 8 and 9 (8+). For the SBUV there appears to be somewhat more information at the upper level, and we suggest that the information be presented as the sum of layers 1–5, layers 6, 7, 8, and the sum of layers 9 and 10 (9+). The results for layer 5 from the averaging kernel concept can be misleading for two reasons. The first is that they are computed for a constant a priori profile. The second is that they do not show the contamination of the layer 5 result by misplaced changes from other layers. While in our test case the error in layer 5 is rather large, the results are a function of total ozone for the base profile, surface reflectivity, and solar zenith angle. Situations other than the one we utilized can result in more comparable results for layer 5. The layer 6 and above results were good for the general range of total ozone, solar zenith angle, and reflectivity. Our point is that it is better to depict the difficulties and err on the side of conservatism, for example, depict the actual information inherent within the results.

Table 1. Difference in SBUV Radiance Ratio (Percent per Decade) Deduced From the Trend Retrieval Process for the Composite Trend Profile Perturbation

Wavelength, nm	Radiance Difference
252	1.91
274	2.63
283	3.26
292	3.91
298	4.16
302	4.64
306	7.41

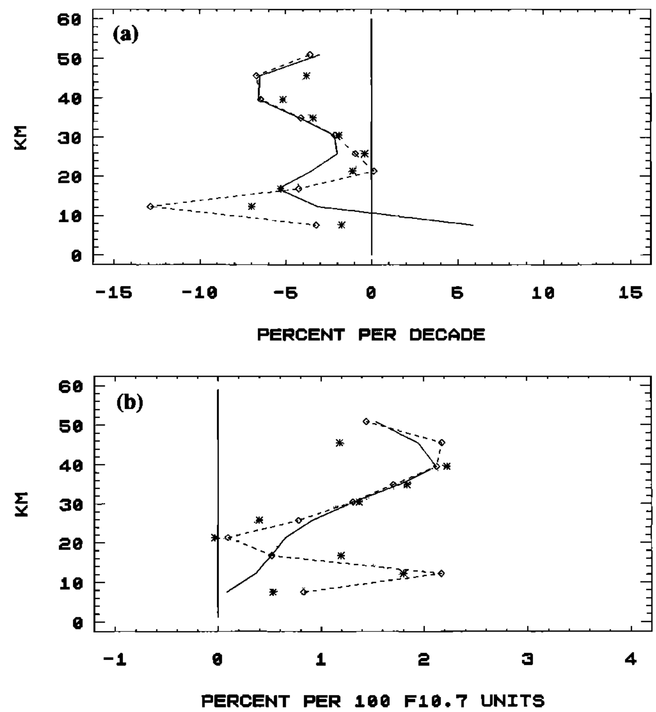

Figure 2. (a) Ozone trends as a function of altitude rederived from Figure 1a in Umkehr layers. Solid line is specified trend, dashed line with diamonds is SBUV, and dotted line with asterisks is Umkehr. (b) Same as Figure 2a for solar coefficients.

The results of combining the information into these layers are depicted in Figures 3a and 3b for the trends and Figures 3c and 3d for the solar effect. Both the specified and retrieved profiles are shown in the new layers. For the SBUV trends in Figure 3a we see that the retrievals match the specified profiles quite well within the 5 layers but that the Umkehr trend results in Figure 3b indicate a divergence due to the substantial difference in layer 9. One could argue that the results are better up to layer 8, neglecting the results in layer 9, but this would make the agreement with the total ozone askew. Looking next at the results for the solar effect (Figures 3c and 3d), we see that both systems are able to retrieve this profile with about the same resolution.

We examine the derived ozone trend and solar response from the combined layer estimates for the SBUV and Umkehr systems and compare the results with both the ozonesonde and SAGE data. For discussion of the statistical treatment of each data the reader is referred to the original articles (*Miller et al.* [1992] for the Umkehr and ozonesonde; *Hollandsworth et al.* [1995] for SBUV, SBUV 2; and *Wang et al.* [1996] for the SAGE I and II). For the Umkehr and ozonesonde data the period of observation is from 1968 to 1991, for the SBUV it is from 1979 to 1991, and for SAGE it extends from 1979 to 1990. As *Miller et al.* [1996] have shown, however, for the Umkehr and ozonesonde data the results from 1968 to 1991 and 1979 to 1991 are similar. In all cases we have stopped prior to the onset of the Mount Pinatubo eruption to avoid possible contamination of the data.

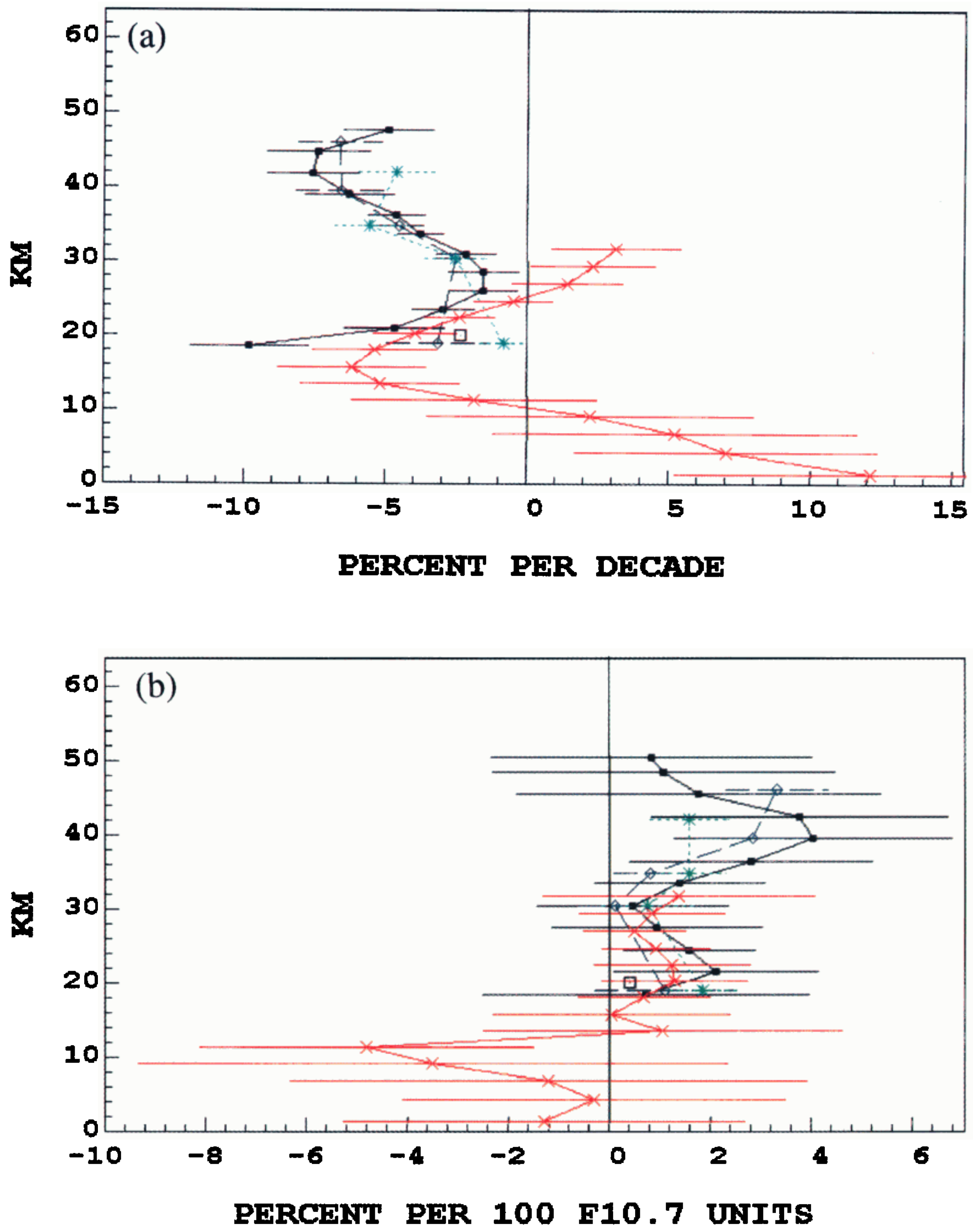

Plate 1. (a) Ozone trends calculated from SBUV (blue dashed curve with diamonds), Umkehr (green dotted curve with asterisks), SAGE (black solid line with points), ozonesondes (red solid line with crosses), and ozonesondes summed over layers 1–5 (purple open box) for midlatitudes of northern hemisphere. For details of computations and length of record, see text. Units are percent per decade. (b) Same as Plate 1a for solar coefficients. Units are percent per 100 F10.7 units.

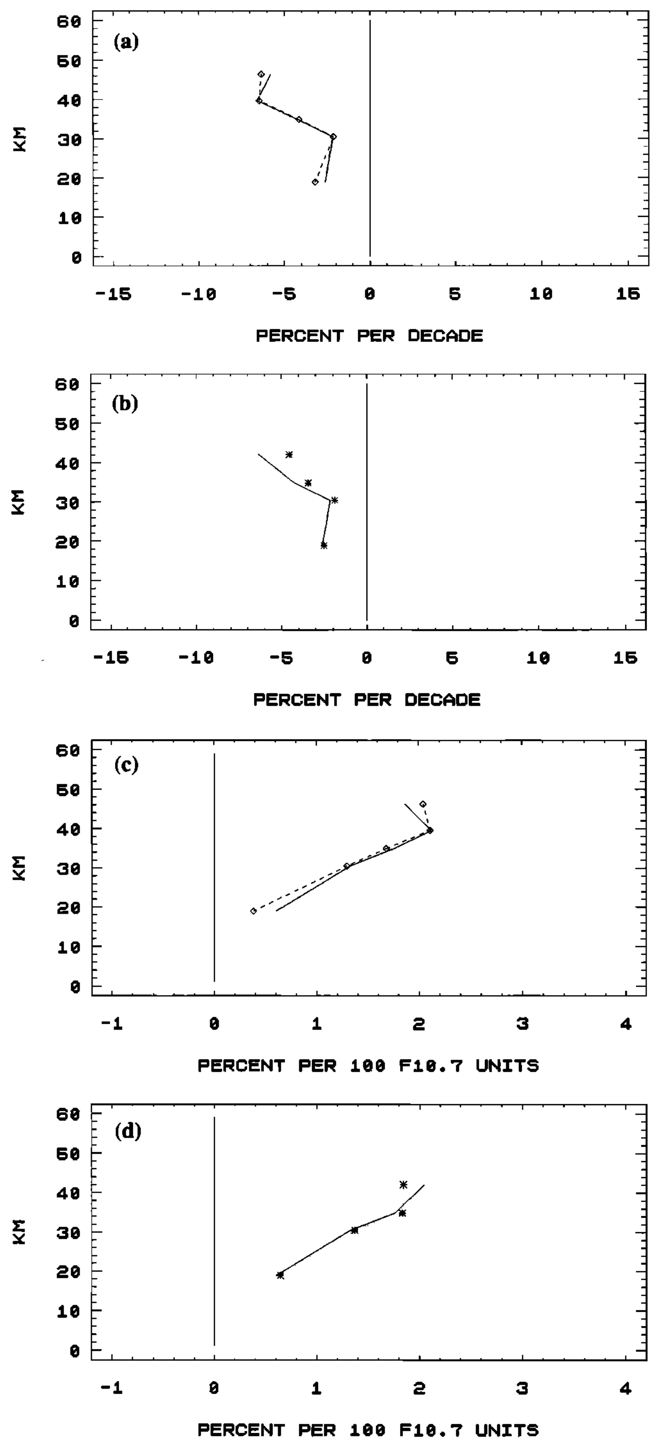

Figure 3. (a) Ozone trends as computed for Figure 2, but depicted as the sum of layers 1–5, and layers 6, 7, 8, and 9+ for SBUV. (b) Same as Figure 3a for Umkehr results in the sum of layers 1–5, and layers 6, 7, and 8+. (c) Same as Figure 3a for SBUV solar estimates. (d) Same as Figure 3b for Umkehr solar estimates.

The results are depicted in Plates 1a (trend) and 1b (solar). For the trend results above 30 km the three estimates agree that a statistically significant trend has occurred (95% confidence level) and that the largest decreases are about −4 to −7% per decade between 40 and 50 km. Note also that the trends agree to within their stated statistical 95% confidence limits. One must be careful not to overinterpret this overlap of statistical error bars, however, as the month-to-month variance in the observations should be highly correlated between measurement systems. A more correct procedure involves determining the trend of the differences between systems to remove the correlated aspects of the data. This is beyond the scope of the present study and will be the focus of future work. At 25 km and above the ozonesonde data indicate an increase in ozone with time in contrast to the other observations which may be related to the sensitivity of the results to changes in the sonde pump efficiency corrections. Below 25 km the results all depict negative trends with SAGE the most negative at about −10% per decade and Umkehr the smallest at about −1% per decade. This latter number is very misleading, however, in that it represents the sum of layers 1 through 5 and we see from the ozonesondes that they indicate a substantial positive trend in the lower troposphere. We have calculated the sonde results for layers 1 through 5 to be about −2% per decade which agrees with the results for SBUV, about −3% per decade, and the Umkehr, −1% per decade. Overall, then, the trend results for the SBUV, Umkehr, and ozonesondes agree in the lower stratosphere. The somewhat larger value obtained by SAGE is just barely outside the 95% confidence limits from the sondes and should be examined further. One additional point that should be mentioned relates to the differences between the SBUV and SBUV 2 instruments. The shortest wavelength channel on the Nimbus 7 SBUV instrument, 255 nm, suffered from contamination due to nitric oxide interference and was not used in the retrieval algorithm. Comparisons of the layer 9 results for SBUV and SBUV 2 on NOAA 11 (which moved the affected channel to 252 nm and avoid this effect) indicated that a bias existed between the two data sets but that they were highly correlated. The biases were removed in the trend determinations by *Hollandsworth et al.* [1995]. Layer 10 does show some significant differences.

The solar results, depicted in Plate 1b, are presented on a scale consistent with the ozonesondes. We see in this diagram that all three systems indicate significant solar effect in the 40 km region, of the order of 2 to 4% per 100 F10.7 units. Above this the SAGE indicates a decrease in response, whereas the SBUV is of the same magnitude. The error bars are such, however, that the two estimates are not significantly different. We also note that all three systems show a relative increase of the solar response coefficients below about 30 km and that the general agreement with the ozonesondes in this area is very good. With the relatively large error bars inherent in the calculations, however, this result should not be argued forcefully. We note, for example, that the sondes indicate a very marked negative coefficient at about 10 km which has not been presented in theoretical models. While this must be examined further, *Miller et al.* [1995] noted that it is consistent in the two time periods 1968–1991 and 1979–1991. In addition, we have calculated the sonde solar coefficient for the sum of layers 1–5, and it is about 0.4% per 100 F10.7 units. This is somewhat smaller than either the SBUV or Umkehr results and suggests that the large negative values at 10 km are, indeed, a manifestation of some other effect. It is true that an impact on the atmospheric ozone due to El Chichon can possibly be aliased in regression model solar terms in that a solar minimum occurred after the eruption. Several groups are examining ways to remove such an effect. For the analysis presented here we note that *Miller et al.* [1996] have shown that the solar analysis results are extremely consistent when analyzed from either

1968 or 1979 (i.e., adding an additional solar cycle). This must be examined further.

Summary

Through examination and simulation of independent, reasonable ozone trend and solar effect profiles, we have ascertained that the Umkehr data contain at most only four independent data points in the vertical and that the SBUV system contains five. Consideration of the trends and solar coefficients should be restricted to the sum of Umkehr layers 1–5, layers 6, 7, and 8+ for the Umkehr, and the sum of layers 1–5, and layers 6, 7, 8, and 9+ for SBUV. We have compared the actual trends and solar coefficients derived in these layers for the periods 1968–1991 and 1979–1991 for the ground-based and satellite data, respectively. As an additional test, we have included the SAGE I and II results from *Wang et al.* [1996] (1979–1990) within the latter comparisons.

For the trend results, above 30 km the SBUV, Umkehr, and SAGE data all show a statistically significant trend with the maximum values between 40 and 50 km of about −4 to −7% per decade. Also, the trends agree to within their stated statistical 95% confidence limits. At 25 km and above, the ozonesonde data indicate an increase in ozone with time in contrast to the other observations which may be related to the sensitivity of the results to changes in the sonde pump efficiencies. Below 25 km the results all depict negative trends with SAGE the most negative at about −10% per decade and Umkehr the least negative at about −1% per decade. This latter number is misleading, however, in that it represents the sum of layers 1 through 5 and the ozonesondes indicate a substantial positive trend in the lower troposphere. We have calculated the sonde results for layers 1 through 5 to be about −2% per decade which agrees quite well with the results for SBUV, about −3% per decade, and the Umkehr, −1% per decade. Overall, then, the trend results for the SBUV, Umkehr, and ozonesondes agree in the lower stratosphere. The somewhat larger value represented by SAGE is outside the 95% confidence limits from the sondes and will have to be examined further.

The solar results for the SBUV, Umkehr, and SAGE all show positive values in the lowest region (sum 1–5), and the ozonesonde results are in relative agreement. With the relatively large error bars inherent in the sonde calculations, however, this result should not be argued forcefully.

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